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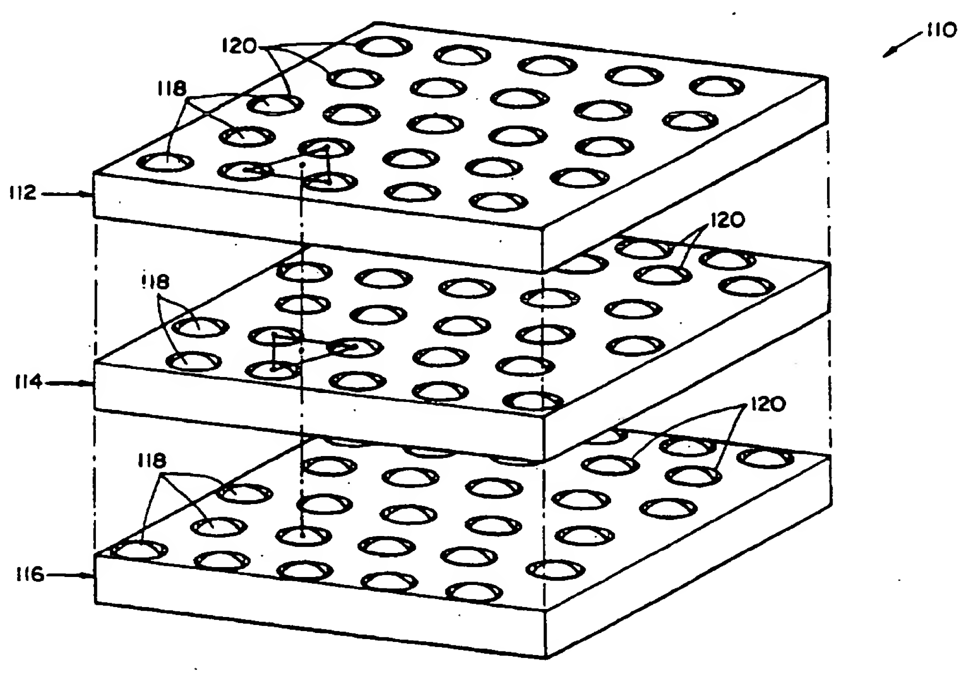
(57) Abstract



A preferred metallodielectric photonic crystal structure includes a three-dimensionally periodic lattice structure of high-electrical-conductivity metallic elements arranged to produce a photonic band gap which defines a range of frequencies of electromagnetic radiation which are prevented from propagating through the photonic crystal structure. The metallic elements are unconnected and arranged in a background of dielectric material. In one embodiment, the dielectric material is made of a plurality of sheets of dielectric with cylindrical holes drilled through the sheets in a two-dimensionally periodic pattern. The high-conductivity metallic elements, such as metallic spheres, are located in the cylindrical holes. The dielectric sheets are stacked so as to arrange the metallic elements in a three-dimensionally periodic crystal lattice structure such as a face-centered cubic lattice structure. The structure can also be fabricated using integrated circuit microfabrication techniques. Alternating layers of dielectric support material and metallic elements are formed in patterns to create the desired three-dimensional periodic lattice structure. Again, the metallic elements do not contact each other. The advantage of the microfabricated structure is that it can be easily scaled down in size to produce photonic stop bands at infrared or, perhaps, visible wavelengths.

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METALLODIELECTRIC PHOTONIC CRYSTAL

Background of the Invention

Photonic crystals are of great interest in the field of electromagnetics because certain types of photonic crystals exhibit a photonic band gap or stop band. The band gap defines a range of frequencies at which electromagnetic radiation striking the crystal is reflected by the crystal rather than being permitted to propagate through it.

The typical photonic crystal is a spatially periodic structure. One well-known photonic crystal is formed of multiple elements of a dielectric material arranged in a three-dimensional lattice. Other crystals exhibit two-dimensional periodicity in which elongated, e.g. cylindrical, elements made of dielectric material are arranged in a two-dimensional periodic pattern with their longitudinal axes parallel to each other.

In these crystals, the dimensions of the lattice structures and the dielectric elements are selected to produce band gaps having desired center frequencies and bandwidths. Electromagnetic radiation at a frequency within the band is reflected from the structure via the well-known Bragg reflection phenomenon.

Summary of the Invention

The present invention is directed to a new photonic crystal structure which provides a frequency band gap defining a range of frequencies at which electromagnetic radiation is prevented from propagating through the crystal. The new structure includes a plurality of

elements of high electrical conductivity arranged in a three-dimensional lattice and being physically, and thus electrically, separated from each other.

In a preferred embodiment, the high-conductivity elements are surrounded by a dielectric background material such as a polymer, a plastic such as Teflon®, a synthetic dielectric such as Stycast® 12, or a semiconductor such as silicon, gallium arsenide, or the like. In one embodiment, the dielectric background is formed as a plurality of dielectric sheets, with each sheet representing a single layer of the three-dimensional lattice structure. Each sheet has a two-dimensional pattern of cylindrical holes formed through it, such as by drilling. A high-conductivity element, such as a metallic spherical ball, is placed in each hole or some predefined subset of holes. The sheets are then stacked on top of each other so as to arrange the spherical balls separate from each other in the predetermined three-dimensional periodic lattice structure. In a preferred embodiment, the holes in each sheet are formed in a two-dimensional triangular lattice structure. The sheets are arranged such that the completed structure forms a close-packed face-centered cubic lattice structure in which the high-conductivity elements are separated from each other.

In another embodiment, the three-dimensional lattice structure is formed using integrated circuit photolithographic and microfabrication technology. In this embodiment, alternating layers of dielectric and metal are formed over a dielectric substrate. In one embodiment, a layer of polymer is first formed over the dielectric substrate, and a thin film of metal such as aluminum is then formed on top of the polymer. Photolithographic techniques are then used to pattern the thin film of metal to produce a two-dimensionally periodic pattern of metal elements, preferably a triangular lattice pattern. Next,

another layer of polymer is formed over the pattern of metal elements, followed by another layer of thin metal film. The metal film is again patterned to produce a two-dimensional triangular lattice pattern above the first metal layer laterally located to form the second layer in the three-dimensional periodic lattice, preferably a close-packed face-centered cubic lattice. Another layer of polymer is formed over the second layer of metal elements, and a third layer of metal is formed over the polymer. Once again, the metal layer is patterned by photolithographic and microfabrication techniques to produce a third two-dimensional triangular lattice pattern of elements located so as to complete the third layer of the three-dimensional fcc lattice.

The metallodielectric photonic crystal (MDPC) of the invention provides a controllable frequency stop band, making it useful in many applications. In the embodiment which uses stacked dielectric sheets, the geometric dimensions of the lattice, such as the sheet thickness, the element diameter and the element spacing, and the material characteristics such as the dielectric constant of the dielectric material, can be varied to select a desired band gap width and center frequency. In the integrated circuit embodiment, the sizing and spacing of the elements can be very precisely controlled, resulting in highly controllable stop band widths and center frequencies. Also, the elements can be made very small and packed very close together, resulting in very high band gap center frequencies extending into the near-infrared and visible ranges.

The three-dimensional photonic crystal structure of the invention has many different applications. It can be used as the substrate for various electrical, electromagnetic and optical circuits. In such circuits, the photonic crystal of the invention prevents energy

losses and cross-coupling between circuits through the substrate. The structure can also be used as the substrate for planar antennas and phased arrays of antennas. By preventing electromagnetic energy from propagating into the substrate, the photonic crystal structure provides for extremely efficient coupling between transmitting/receiving circuitry and free space via the planar antenna.

Also, the integrated circuit embodiment can be used as a filtering thin film which is dimensioned to block certain selected wavelengths of light. For example, the structure can be used as a coating for windows of a building to facilitate environmental control. That is, the structure can be produced to block heat in the form of infrared radiation from travelling out of the building through the windows. Also, certain wavelengths of radiation can be blocked from entering the building while visible light is allowed to pass for illumination.

The MDPC of the invention can be manufactured quickly and efficiently. In the stacked sheet embodiment, the sheets are made by stacking them together and then drilling holes through all of the sheets simultaneously in the triangular lattice pattern. After the metallic elements have been placed in the holes, the sheets are laterally offset as they are stacked to provide the three-dimensional periodicity. In a prior three-dimensional photonic crystal structure, the structure was formed by drilling a complicated pattern of holes through the entire block of material at various angles relative to the top surface of the block. A typical three-dimensional structure required hundreds of hours of machine shop time to produce the structure. The integrated circuit embodiment can also be very efficiently fabricated. Well-known photolithography techniques can be used in a production environment to fabricate the devices in large quantities at low cost.

Brief Description of the Drawings

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

FIG. 1 is a schematic perspective view of the three-dimensional metallodielectric photonic crystal of the invention lying on a face-centered cubic lattice.

FIG. 2 is a schematic top view of the face-centered cubic metallodielectric photonic crystal structure of FIG. 1.

FIG. 3 is a schematic perspective exploded view of an embodiment of the invention comprising stacked dielectric sheets containing metallic atoms of the three-dimensional periodic structure of the invention.

FIGs. 4A-4D are plots of the transmission characteristic of the dielectric background material of the stacked-dielectric-sheet embodiment of the face-centered cubic metallodielectric photonic crystal of the invention.

FIGs. 5A-5D are plots of the transmission characteristic of an embodiment of the face-centered cubic metallodielectric photonic crystal structure of the invention using the background material used for the plots of FIGs. 4A-4D.

FIG. 6 is a plot of the transmission characteristic of the face-centered cubic embodiment of the metallodielectric photonic crystal of the invention having different geometric dimensions than the embodiment of FIG. 5.

FIG. 7 is a plot of the transmission characteristic of the face-centered cubic embodiment of the metallodielectric

photonic crystal of the invention having different geometric dimensions than the embodiment of FIG. 5.

FIGs. 8A-8I are schematic cross-sectional illustrations showing fabrication steps used to produce an integrated circuit embodiment of the three-dimensional metallodielectric photonic crystal of the invention.

Detailed Description of the Invention

FIG. 1 is a schematic perspective view of a preferred embodiment of the three-dimensional photonic crystal structure 10 of the invention. The structure shown in the figure includes three layers 12, 14 and 16 of high-electrical-conductivity spherical elements 18. In this embodiment, the spheres 18 are arranged in a close-packed face-centered cubic lattice. Three layers 12, 14 and 16 are shown to completely illustrate one period of the lattice. However, it will be understood that more than three layers can be used. While the spheres 18 are close-packed, they are maintained at a distance away from each other such that they do not touch. It should be noted that different shading is used in the drawings to distinguish between layers of elements 18. However, the spherical elements 18 are preferably all made of the same material, for example, a high-electrical-conductivity metal such as chrome steel, brass, carbon steel or stainless steel.

The electrical conductivity of brass is 2.564×10^7 S/m at 20°C. For chromium, the conductivity is 3.846×10^7 S/m, and for stainless steel, the conductivity is 1.1×10^6 S/m. (see David M. Pozar, *Microwave Engineering*, Addison-Wesley Publishing Co., 1990). For the metallodielectric photonic crystal of the invention, the high-electrical-conductivity elements 18 should have similar conductivities. The electrical conductivity of the elements should preferably be above 1×10^6 S/m.

FIG. 2 is a schematic top view of the three-dimensional photonic crystal structure 10 of FIG. 1. FIG. 2 schematically illustrates the spatial relationships among the individual layers 12, 14 and 16 of the structure 10. As shown in the drawing, each layer comprises a two-dimensional periodic arrangement of spherical elements 18. In the embodiment shown, the two-dimensional periodic arrangement is a triangular lattice with lattice constant t representing the distance between centers of the elements 18. As shown, each element in the middle layer 14 is located beneath the center of a triangle defined by elements of the top layer 12. Likewise, each element in the bottom layer 16 is located beneath the center of a triangle defined by elements in the top layer 12. This arrangement of elements 18 produces a close-packed face-centered cubic lattice structure.

The lattice structure 10 shown in FIGs. 1 and 2 exhibits a forbidden frequency range or frequency band gap or stop band which defines a range of frequencies of electromagnetic radiation which is prevented from propagating through the structure 10. Electromagnetic energy having a frequency outside of the stop band propagating as indicated by arrow 20 (see FIG. 1) passes through the structure and continues to propagate as indicated by arrow 22. However, electromagnetic energy having a frequency within the frequency stop band is reflected by the structure 10.

FIG. 3 is a schematic perspective exploded view of a preferred embodiment 110 of the invention. In this embodiment, the structure 110 includes a plurality of sheets 112, 114, 116 of dielectric material stacked on top of one another. The dielectric material can be a plastic, a polymer, a synthetic dielectric such as Stycast® 12, or it can be a semiconductor material. Each sheet 112, 114, 116 comprises a plurality of cylindrical holes 120 through

the sheet. The holes 120 are arranged in the two-dimensional periodic triangular lattice pattern described above. A high-conductivity element such as a spherical metal ball 118 is placed in each hole 120 or a predetermined subset of the holes. The sheets 112, 114 and 116 of dielectric material are stacked on top of each other to form the three-dimensional close-packed fcc lattice of the high-conductivity metallic elements 118. The holes 120 and sheets 112, 114 and 116 are therefore positioned relative to each other such that the elements 118 are separated from each other and form the fcc lattice structure.

The close-packed condition for the fcc lattice results when the triangular lattice constant t is related to the sheet thickness s by $t = \sqrt{\frac{3}{2}}\, s$. The fcc conventional cubic lattice constant a is then given by $a = \sqrt{2}\, t$.

FIGs. 4A-4D and 5A-5D illustrate results of experiments performed on the three-dimensional photonic crystal structure of the invention in the embodiment of FIG. 3. The structure used for the experiments was made from three sheets of 1/4 inch thick Stycast® 12 synthetic dielectric. The holes formed through the Stycast® were approximately 1/4 inch in diameter and were arranged in the two-dimensional triangular lattice pattern having a lattice constant t of 7.8 mm or 0.306 inches. FIGs. 4A-4D and 5A-5D show the transmission characteristics of the structure in a frequency range between 2.0 and 26.0 GHz. FIGs. 4A-4D show the transmission characteristics without any metallic elements 118 in the holes 120. That is, the structure used to produce the results of FIGs. 4A-4D consisted only of three sheets of synthetic dielectric material with a three-dimensionally periodic pattern of cylindrical void regions in the material. FIGs. 5A-5D show the results with

spherical high-conductivity metallic elements in each of the holes 120. The elements used were 1/4 inch diameter "chrome steel balls" manufactured by McMaster-Carr of New Brunswick, New Jersey.

To produce the results of FIGs. 4A-4D and 5A-5D, the electromagnetic transmission through the two individual structures was measured from approximately 2 to 26 GHz with an HP8510 network analyzer. A set of four feed horns operating in S, C, X and K bands was used to transform the radiation from coaxial cable to free space and vice versa. The fcc photonic crystals were both placed between the feed horns with their front and back (111) facets, i.e., top or bottom layers, perpendicular to the beam propagation direction.

Referring to FIGs. 4A-4D, each plot compares the transmission characteristics of the photonic crystal (PC) with those of free space (air). It is noted that with no metallic elements present, there is insignificant difference in the transmission through the crystal and through free space between about 2 and 17 GHz. Between about 17 and 19 GHz there is shown a feature that has a maximum rejection of approximately 10 dB and a width of about 2 GHz. This is thought to be the photonic band gap or stop band of the three-dimensional periodic dielectric structure without metallic elements. This stop band is due to the well-known Bragg scattering effects found in purely dielectric photonic crystal structures. Above 19 GHz in the plot of FIG. 4D, there are three sharp features located at approximately 22.5, 24.0 and 25.4 GHz. All of these are believed to be associated with a higher band gap or band gaps in the dielectric photonic crystal.

Once again, FIGs. 5A-5D show the transmission characteristics for the photonic crystal structure of the invention with the metallic high-conductivity elements 118 inserted in the holes 120 of the Stycast® sheets. The

plots compare the characteristics for the metallodielectric photonic crystal (MDPC) with those of free space (air). The most fundamental difference between FIGs. 4A-4D and 5A-5D is the significant rejection feature of the MDPC starting at about 3.2 GHz in FIG. 5A, extending up through C band and well into the X band data of FIG. 5C, and stopping at about 13 GHz.

As shown in FIG. 5C, the MDPC also exhibits a narrow rejection feature of about 10 dB around 16.8 GHz. This is thought to correspond to the dielectric photonic band gap between 17 and 19 GHz in the dielectric photonic crystal shown in FIGs. 4C and 4D. In FIG. 5D, the MDPC of the invention shows further rejection features at about 21.0, 23.0 and 25.0 GHz. These are associated with the upper photonic stop bands shown for the dielectric photonic crystal in FIG. 4D.

The new rejection feature realized in the metallodielectric photonic crystal 110 of the invention is related to the difference in electromagnetic scattering between dielectric atoms of the prior art and the metallic atoms of the present invention. In the case of spherical atoms, it is known that both dielectric and metallic spheres exhibit little effect on electromagnetic radiation at wavelengths which are much greater than the diameter of the sphere. However, as the wavelength decreases, both types of spheres begin to scatter radiation much more efficiently. In fact, it is known that the scattering cross-section σ varies with wavelength as $\frac{1}{\lambda^4}$. The work of Mie showed that at wavelengths just greater than the sphere diameter, most of the scattered radiation from dielectric spheres occurs in the forward direction. In contrast, at the same wavelength in metallic spheres, most of the scattering occurs in the reverse direction, even though

there is a small Mie effect. The Mie effect is described in optics textbooks such as *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*, Sixth (Corrected) Edition, pp. 632-659, by Max Born and Emil Wolf, published by Pergamon Press, which is incorporated herein by reference.

Another relevant result of Mie's work was that the scattering cross-section approaches a maximum when the wavelength satisfies the Mie relation $\frac{\pi D n_e}{\lambda_o} = 1$; where D is the diameter of the sphere, n_e is the effective index of refraction at the surface of the sphere, and λ_o is the wavelength of the radiation in free space. In the examples described above, the lower edge of the stop band of the metallodielectric photonic crystal of the invention is in approximate agreement with the Mie relation.

Variations of the three-dimensional photonic crystal of the invention have also been fabricated and tested. FIGs. 6 and 7 show transmission characteristics of two such variations. FIG. 6 is the characteristic of an L-band metallodielectric photonic crystal. The device was made from three plates of synthetic dielectric Stycast® 12 which were each one foot square and one inch thick. The scattering elements were 3/4 inch diameter carbon steel spherical balls. The transmission characteristic of FIG. 6 shows a stop band extending from approximately 1.0 to 2.0 GHz and having a maximum rejection of about 10 dB.

FIG. 7 shows the transmission characteristic of a structure in accordance with the invention made from three sheets of Teflon® 3/8 inch thick with 3/8 inch diameter carbon steel balls as the scattering elements. This structure exhibits a deep stop band extending from 5.8 to about 14.8 GHz and having a maximum rejection of about 25 dB around 10.0 GHz.

FIGs. 8A-8I illustrate the steps used to fabricate an integrated circuit embodiment 210 of the three-dimensional metallodielectric photonic crystal of the invention. In this embodiment, the photonic crystal structure 210 is fabricated using integrated circuit fabrication techniques. In the first step shown in FIG. 8A, a dielectric layer, such as a planarizing polymer film 212 of polyimide, is formed over a dielectric substrate 214. The substrate material depends upon the application in which the device is to be used. For example, where the eventual stop band is to be in the visible or near-infrared region out to wavelengths of approximately 3 μm, high quality glass or fused quartz can be used since they are transparent at those wavelengths, and they are also highly economical. In the infrared band between 3 and 5 μm, sapphire or high-resistivity silicon are good choices. In the infrared band between 8 and 12 μm, high resistivity silicon or semi-insulating gallium arsenide would both be good choices. In other applications, where a flexible structure is desired, less rigid substrate materials would be better choices.

After the planarizing polymer film 212 is formed, a thin layer 216 made of a metal such as aluminum is formed over the polymer 212. As shown in FIG. 8B, a film of positive polarity photoresist 218 is then formed over the metal. Next, as shown in FIG. 8C, the photoresist 218 is masked, exposed and developed to form plural dots 219 of photoresist in the two-dimensional pattern desired for a single layer of metal elements. In the step shown in FIG. 8D, the metal layer 216 is etched by a known acid material. During the etching, the photoresist dots 219 mask the metal film 216. After the etching step, the photoresist dots 219 are stripped, leaving metal dots 220 in the two-dimensional pattern on top of the polymer layer 212.

Subsequent additional layers of patterned elements are then formed beginning with the formation of another polymer

layer 222 and then another thin metal layer 224 as shown in FIG. 8E. In the next step shown in FIG. 8F, a second layer of metal dots 226 is formed over the polymer layer 222. The second metal film layer 224 is patterned in such a way that the resulting dots 226 are offset in a precise manner with respect to the dots 220 in the layer immediately below, dictated by the desired final three-dimensional structure. For example, if the dots in each layer are patterned in a triangular lattice and layers are offset in a double close-packed fashion, a face-centered cubic lattice results as in the structure described above.

The process repeats again beginning at the step shown in FIG. 8G in which a third planarizing polymer film 228 is formed over the dots 226, which is followed by a third thin metal film 230. Once again, as shown in FIG. 8H, a series of metal dots 232 is formed as desired by photolithographic techniques over the polymer film 228. Finally, as shown in FIG. 8I a layer of insulating polymer 234 is formed over the dots 232 as a capping layer to insulate the structure 210.

The finished three-dimensionally periodic structure 210 is used as described above to produce a photonic band gap defining frequencies which are reflected by the structure 210. It should be noted that FIGs. 8A-8I are schematic only. They are intended to represent the steps required to form the metallodielectric photonic crystal by integrated circuit fabrication techniques. The particular patterns of metal dots shown do not represent any particular crystal lattice structure. It will be understood that the pattern of dots formed at each layer can be altered and controlled as desired to produce any final three-dimensionally periodic lattice structure.

The structure 210 described in connection with FIGs. 8A-8I allows the metallodielectric photonic crystal to be fabricated on very small scales. As such it is applicable

to devices operating in the near-infrared or visible wavelengths as a substrate on which these devices can be isolated from each other. It can also be used as a substrate for planar antennas fabricated by integrated circuit techniques. Also, with a flexible substrate, the structure can be applied as a frequency selective coating to prevent emissions or transmissions of certain wavelengths of radiation. One particular commercial application for it is as a coating for building windows to prevent heat from escaping buildings in the form of infrared radiation.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

CLAIMS

The invention claimed is:

1. A photonic crystal structure comprising:

   a plurality of unconnected high-electrical-conductivity elements arranged with respect to each other in a three-dimensionally periodic lattice structure dimensioned to produce an electromagnetic stop band which defines a range of frequencies at which electromagnetic radiation is substantially prevented from propagating through the lattice structure; and

   a support structure positioning the high-electrical-conductivity elements in the three-dimensionally periodic lattice structure.

2. The photonic crystal structure of Claim 1 wherein the high-electrical-conductivity elements are metallic.

3. The photonic crystal structure of Claim 1 wherein the high-electrical-conductivity elements are spherical.

4. The photonic crystal structure of Claim 1 wherein the support structure is made of a dielectric material.

5. The photonic crystal structure of Claim 1 wherein the support structure comprises a plurality of sheets of dielectric material, high-electrical-conductivity elements being located in each of the sheets.

6. The photonic crystal structure of Claim 5 wherein each sheet comprises a plurality of holes through the sheet in which the high-electrical-conductivity elements are located.

7. The photonic crystal structure of Claim 1 wherein the support structure comprises multiple layers of dielectric material formed over a dielectric substrate.

8. The photonic crystal structure of Claim 7 wherein the high-electrical-conductivity elements are formed from layers of metal interposed between the layers of dielectric material.

9. A three-dimensionally periodic photonic crystal structure comprising:

a plurality of sheets of dielectric material;

a plurality of holes in a two-dimensionally periodic pattern through each sheet of dielectric material; and

high-electrical-conductivity elements located in all or a subset of the holes; wherein

the sheets of supporting dielectric material are stacked on each other to locate the high-electrical-conductivity elements in the three-dimensionally periodic photonic crystal structure.

10. The three-dimensionally periodic photonic crystal structure of Claim 9 wherein the dielectric material is a synthetic dielectric.

11. The three-dimensionally periodic photonic crystal structure of Claim 9 wherein the dielectric material is a polymer.

12. The three-dimensionally periodic photonic crystal structure of Claim 9 wherein the high-electrical-conductivity elements are metallic.

13. The three-dimensionally periodic photonic crystal structure of Claim 9 wherein the high-electrical-conductivity elements are spherical.

14. A three-dimensionally periodic photonic crystal structure comprising:

a first layer of a dielectric material over a substrate;

a first layer of metallic elements formed over the first layer of dielectric material distributed in a two-dimensionally periodic pattern; and

over the first layer of metallic elements, alternating layers of the dielectric material and metallic elements, each layer of metallic elements being distributed in a two-dimensionally periodic pattern such that a plurality of layers of metallic elements form the three-dimensionally periodic photonic crystal structure.

15. The three-dimensionally periodic photonic crystal structure of Claim 14 wherein the dielectric material is a polymer.

16. A method of manufacturing a three-dimensionally periodic photonic crystal structure comprising:

providing a plurality of sheets of dielectric material;

forming a plurality of holes through each sheet of dielectric material in a two-dimensionally periodic pattern;

locating high-electrical-conductivity elements of the photonic crystal structure in all or a subset of the holes; and

stacking the sheets of dielectric material to position the high-electrical-conductivity elements in the three-dimensionally periodic photonic crystal structure.

17. A method of manufacturing a three-dimensionally periodic photonic crystal structure comprising:

forming a first layer of a dielectric material over a dielectric substrate;

forming a first layer of metal over the first layer of dielectric material;

etching the first layer of metal to form a two-dimensionally periodic pattern of metallic elements;

forming successive alternating layers of the dielectric material and metal over the first layer of metal; and

etching each successive layer of metal to form a two-dimensionally periodic pattern of metallic elements in each layer of metal such that the metallic elements are arranged in the three-dimensionally periodic photonic crystal structure.

18. The method of Claim 17 wherein the two-dimensionally periodic pattern of metallic elements in each metal layer is defined by photolithographic and microfabrication techniques.

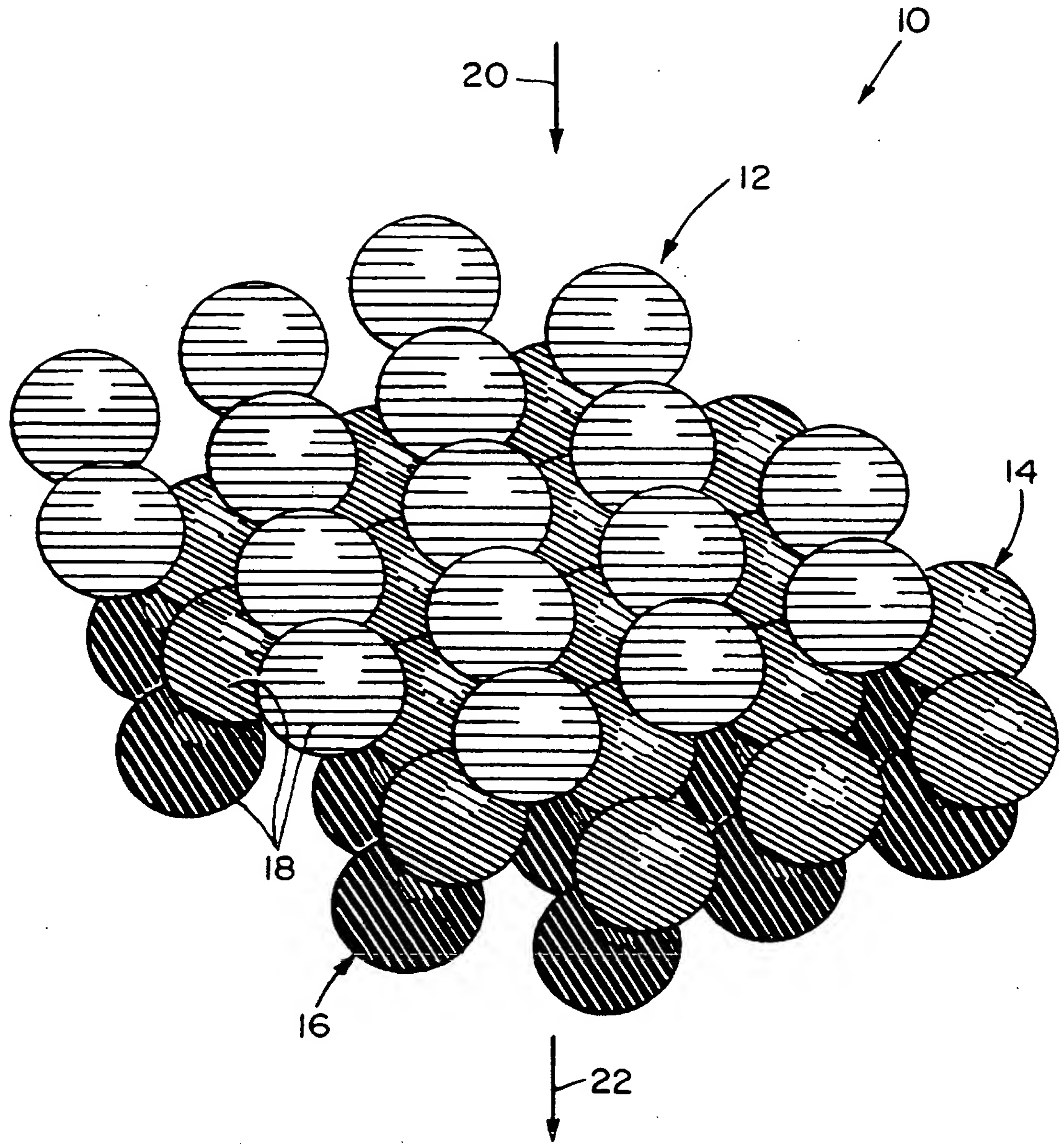


FIG. 1

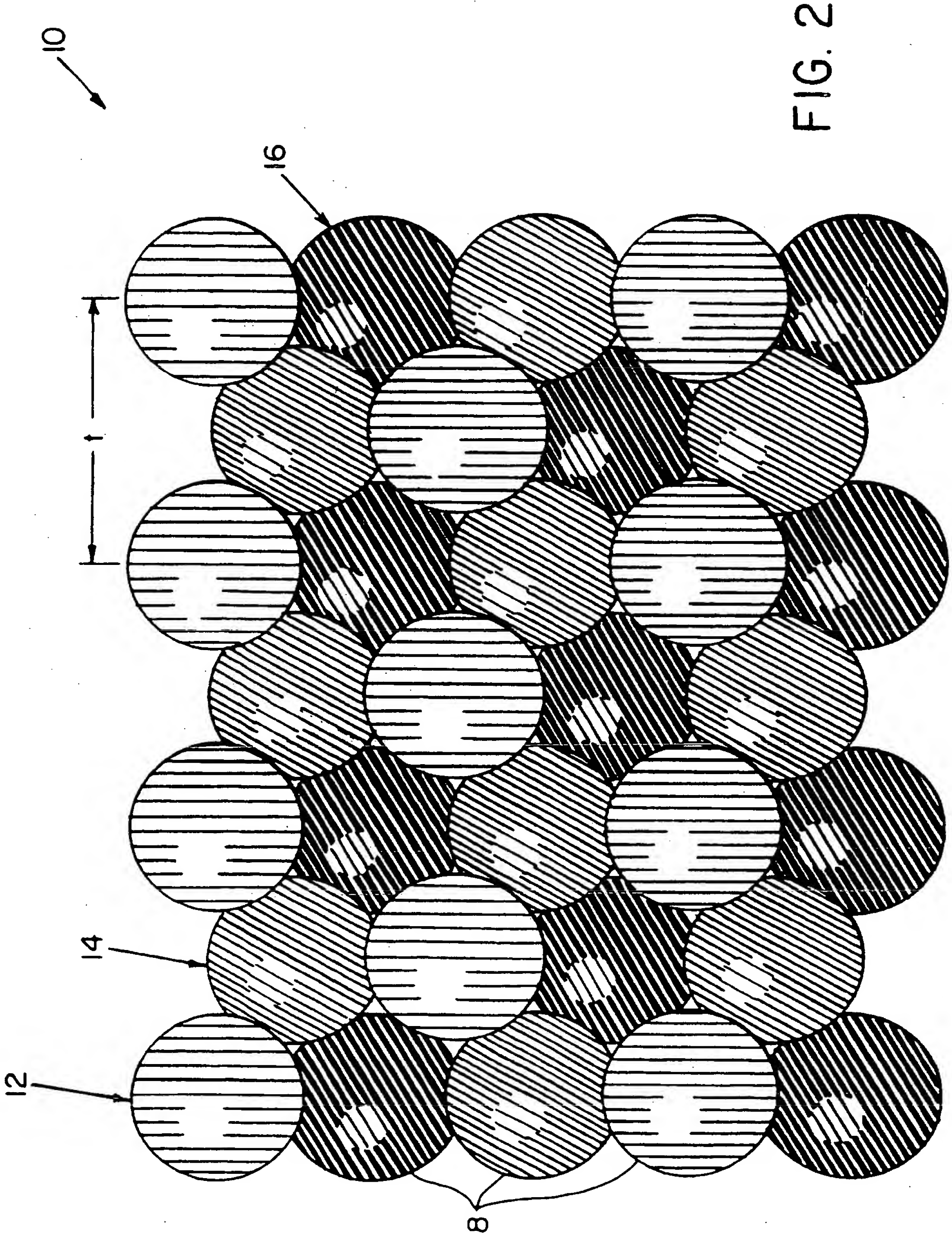


FIG. 2

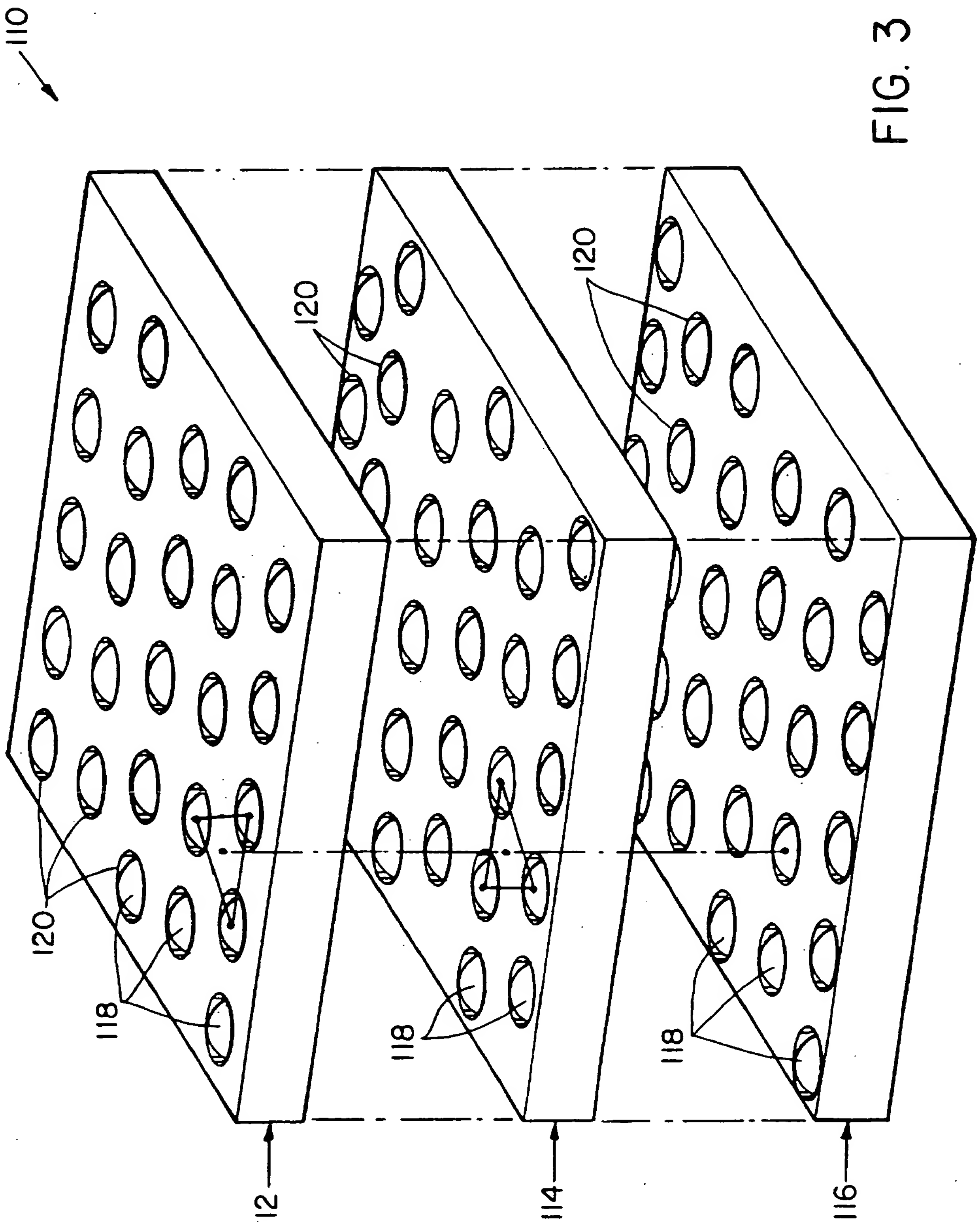
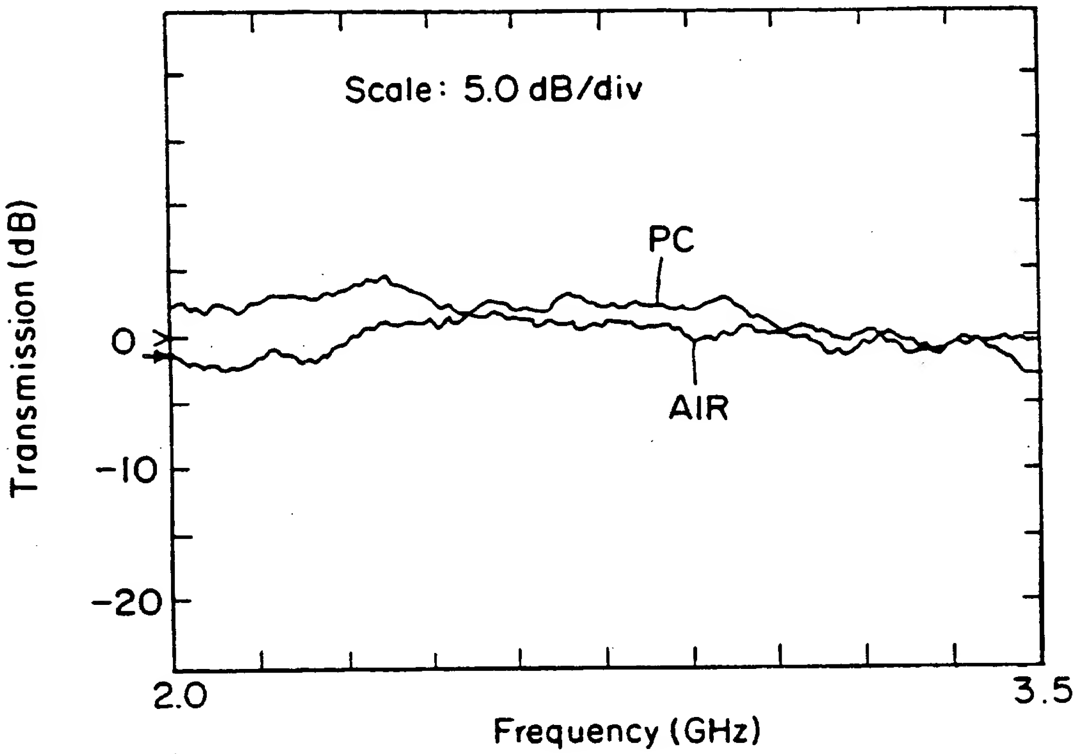


FIG. 3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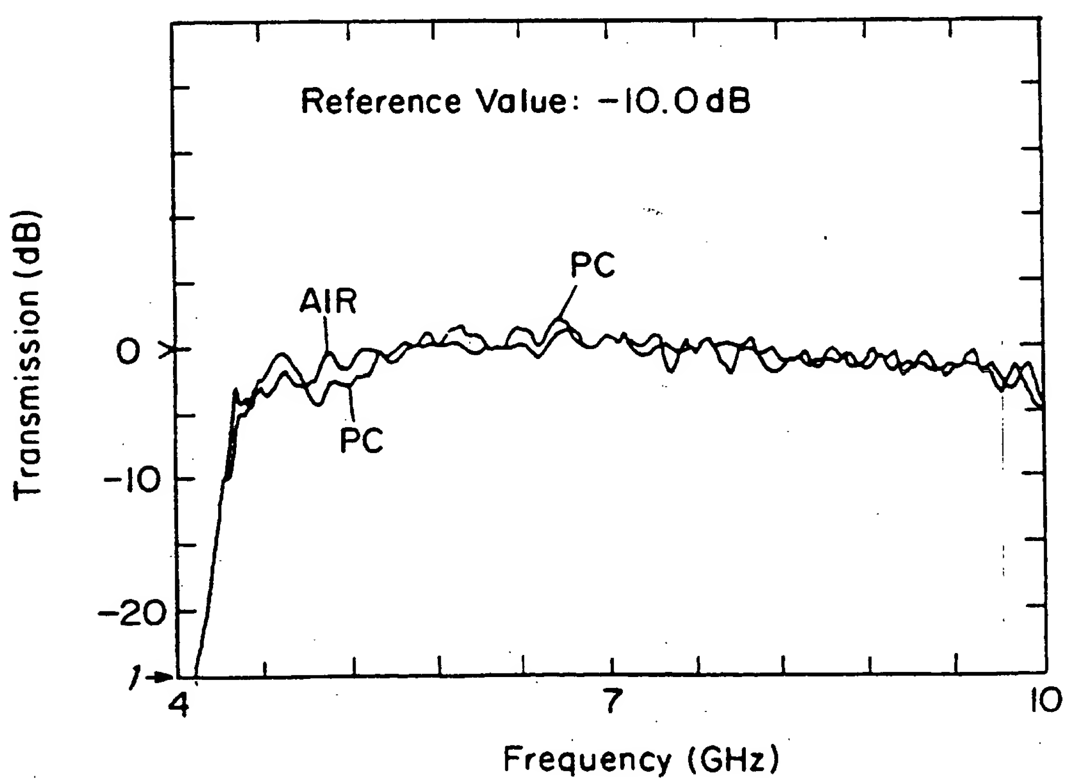
-10
-20
2.0
3.5
Frequency (GHz)

FIG. 4A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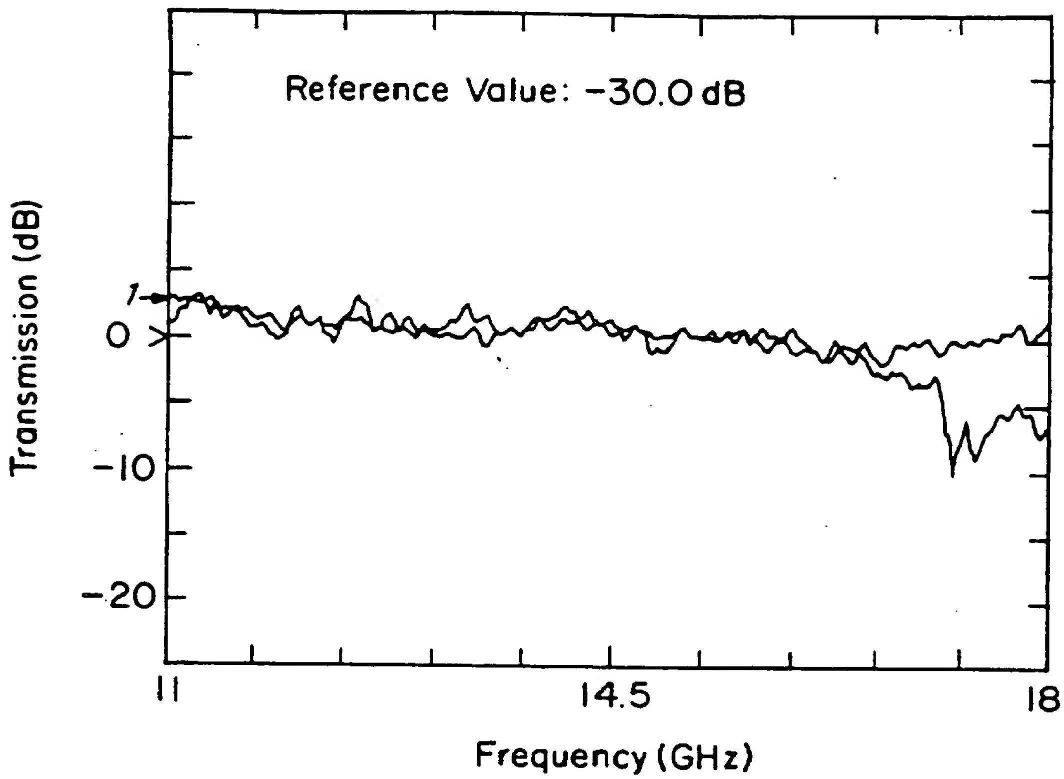
Frequency (GHz)

FIG. 4B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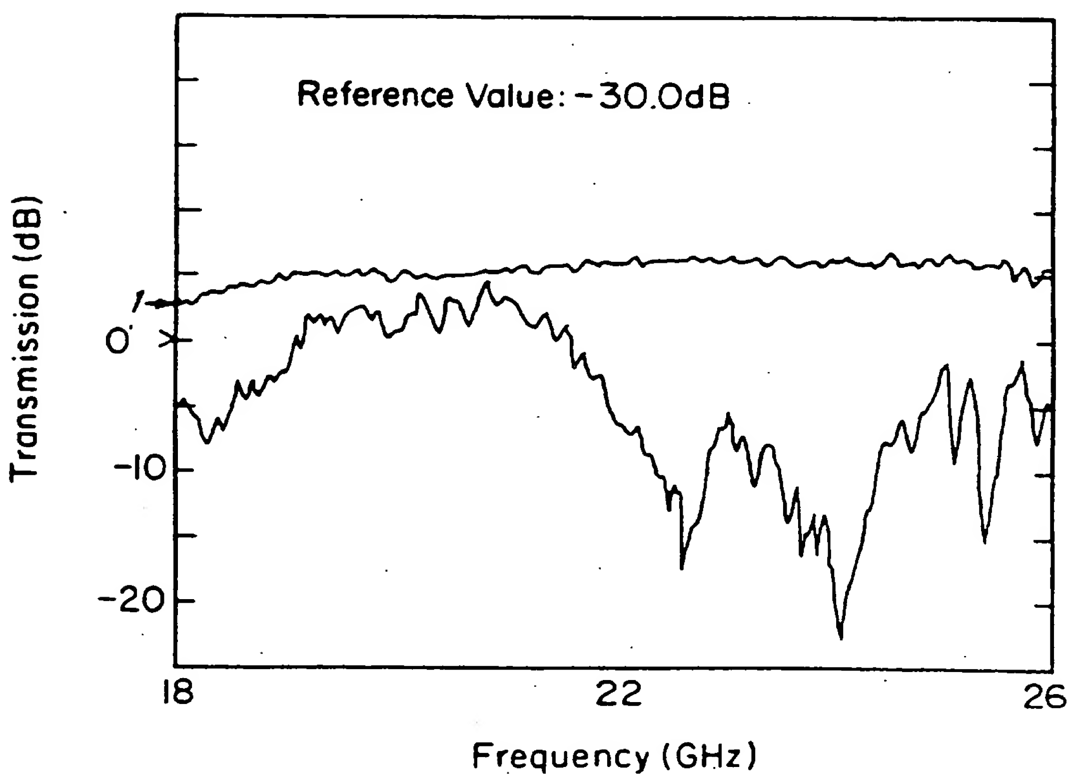
14.5
18
Frequency (GHz)

FIG. 4C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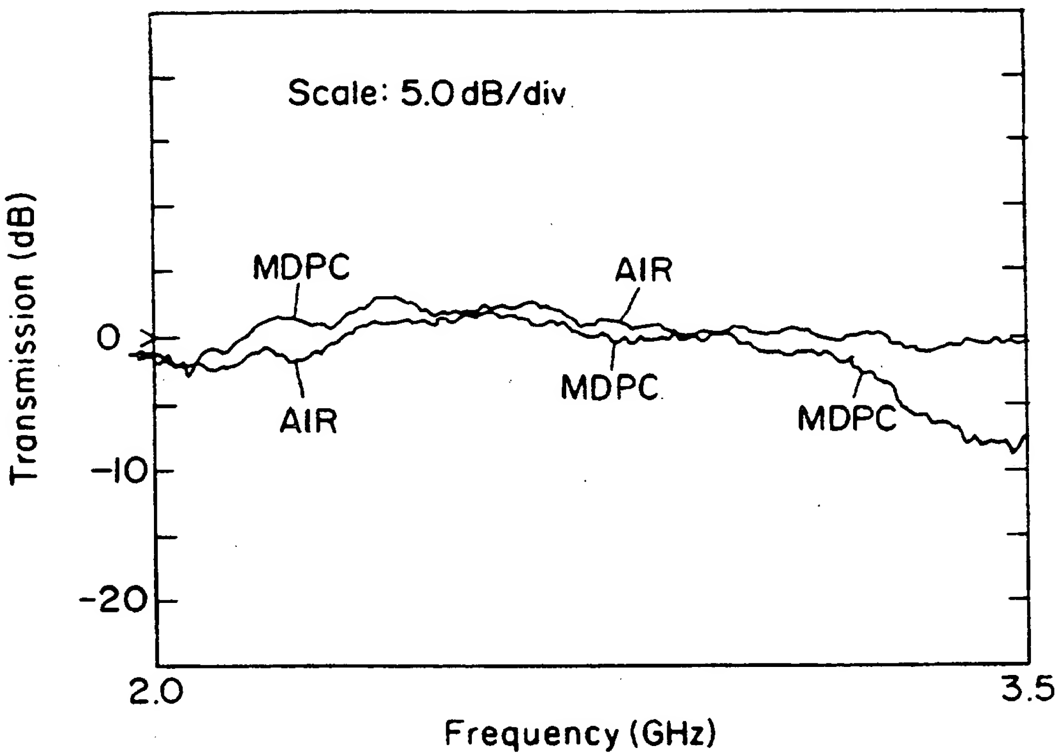
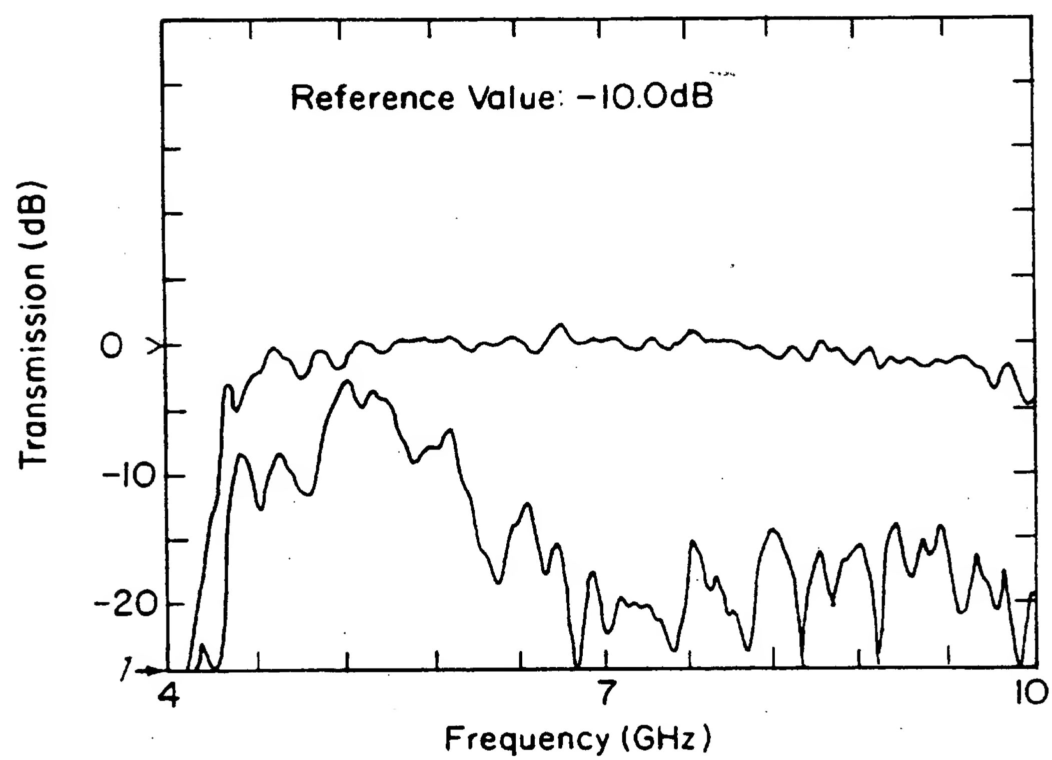
22
26
Frequency (GHz)

FIG. 4D



Scale: 5.0 dB/div
Transmission (dB)
MDPC
AIR
0
AIR
MDPC
MDPC
-10
-20
2.0
3.5
Frequency (GHz)

FIG. 5A



Reference Value: -10.0dB
Transmission (dB)
0
-10
-20
4
7
10
Frequency (GHz)

FIG. 5B

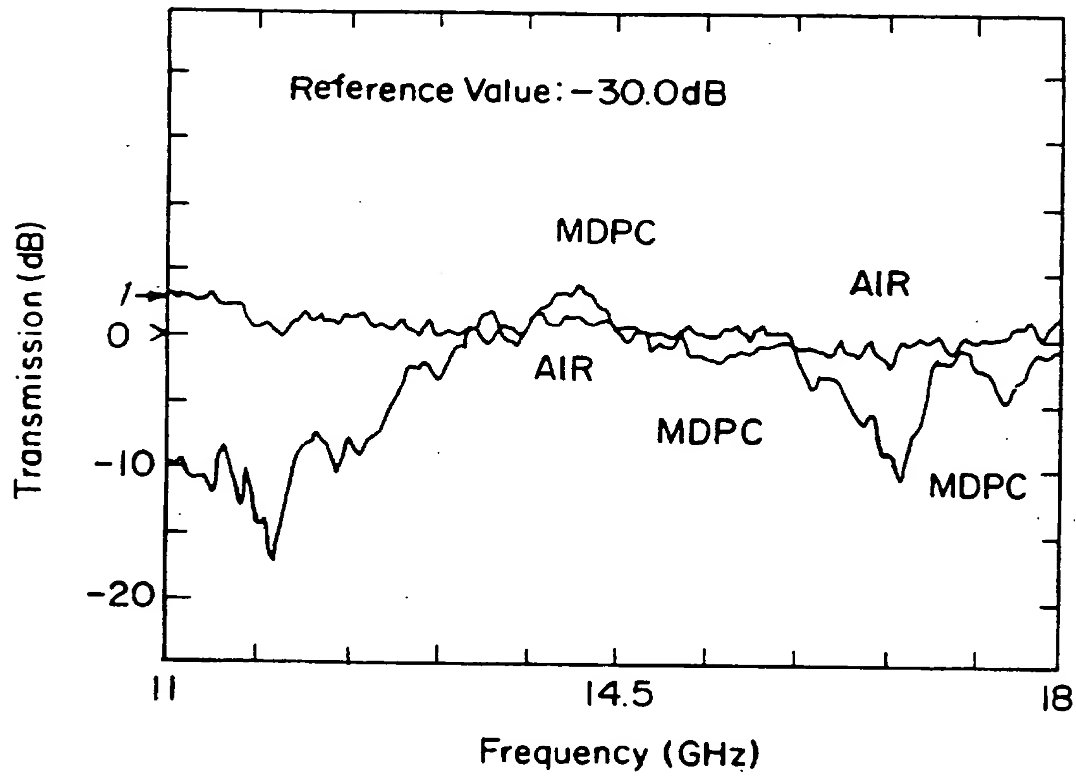

Reference Value: −30.0dB
Transmission (dB)
MDPC
AIR
AIR
MDPC
MDPC
1
0
-10
-20
11
14.5
18
Frequency (GHz)

FIG. 5C

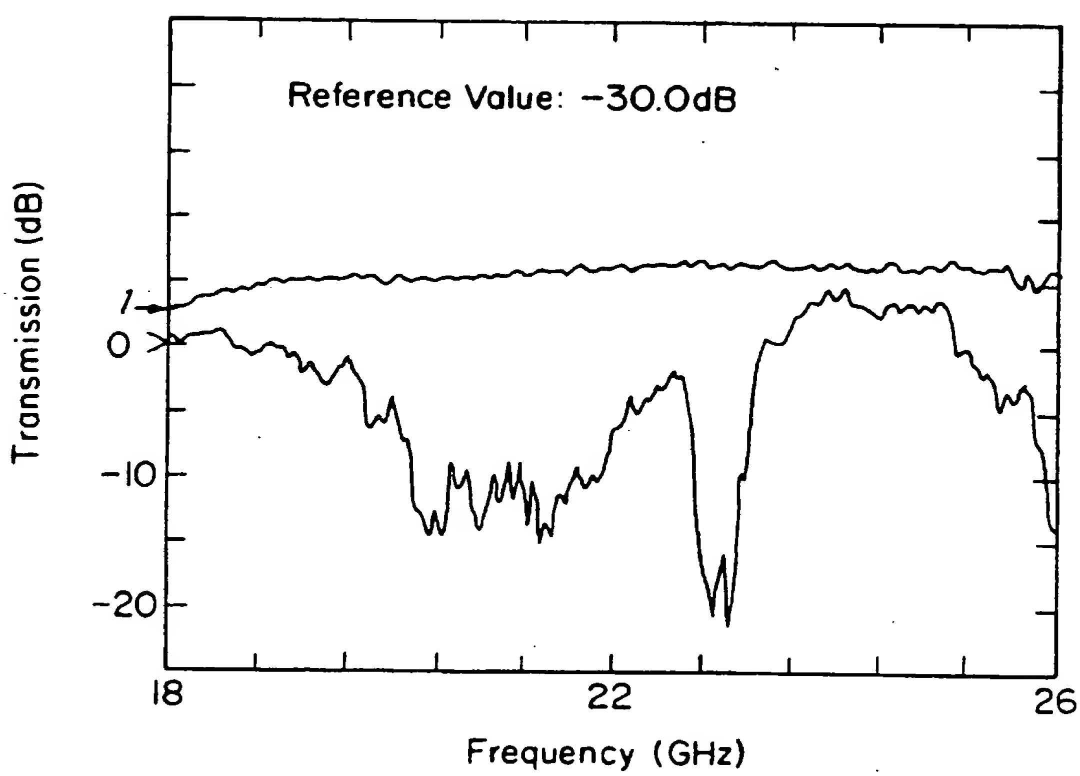

Reference Value: −30.0dB
Transmission (dB)
1
0
-10
-20
18
22
26
Frequency (GHz)

FIG. 5D

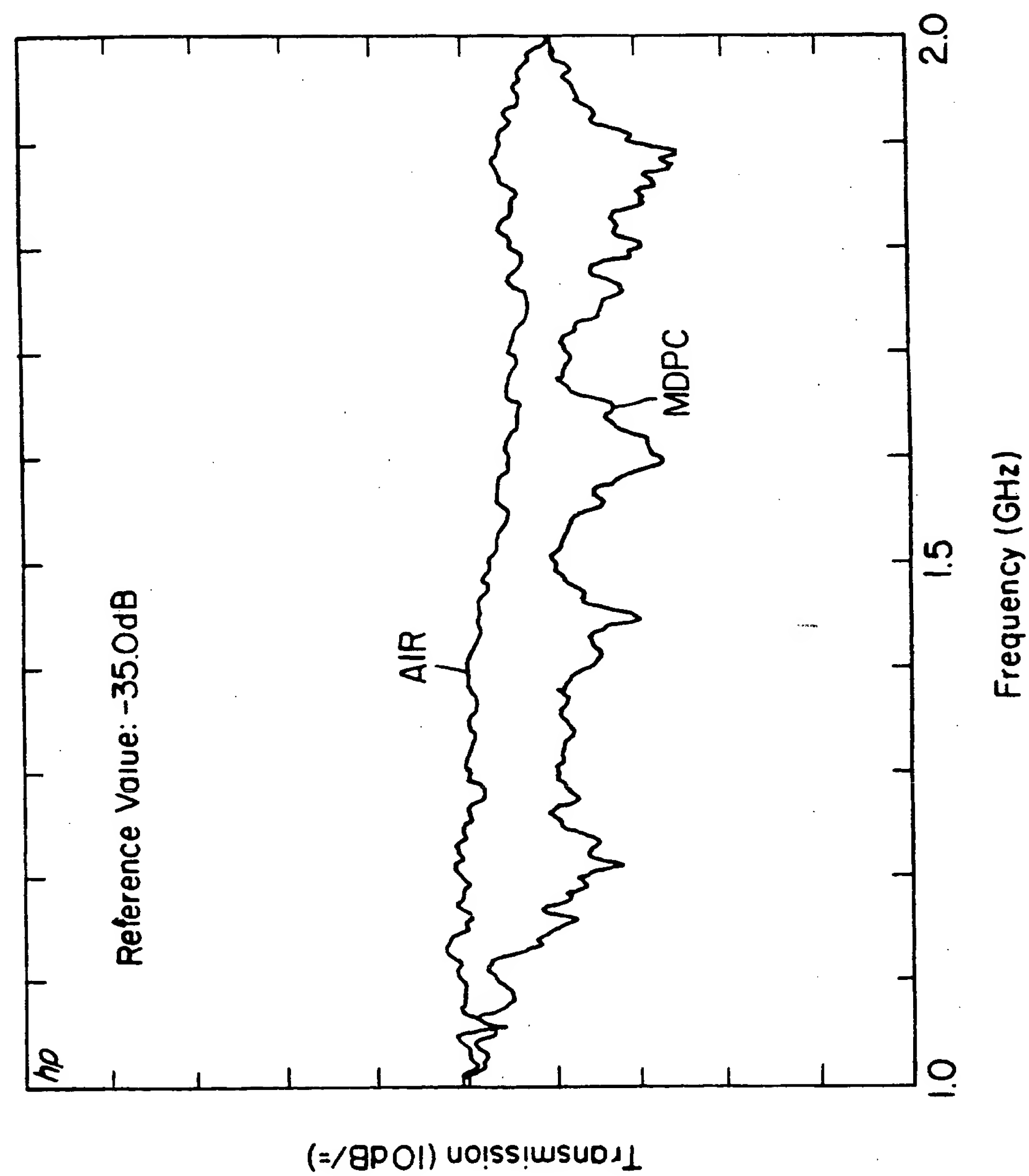

Reference Value: -35.0dB
hp
AIR
MDPC
1.0
1.5
2.0
Frequency (GHz)
Transmission (10dB/=)

FIG. 6

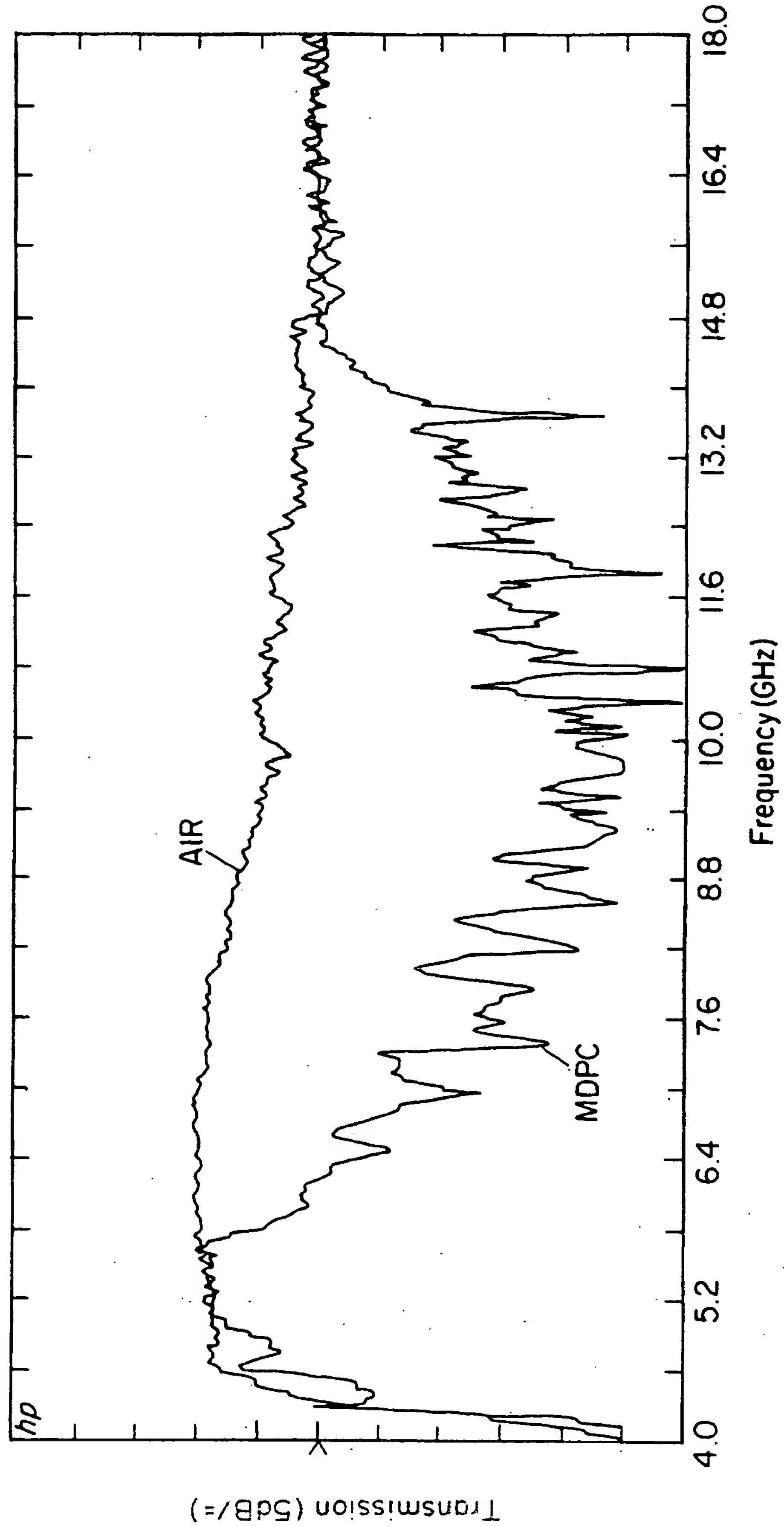

hp
AIR
MDPC
4.0
5.2
6.4
7.6
8.8
10.0
11.6
13.2
14.8
16.4
18.0
Frequency (GHz)
Transmission (5dB/=)

FIG. 7

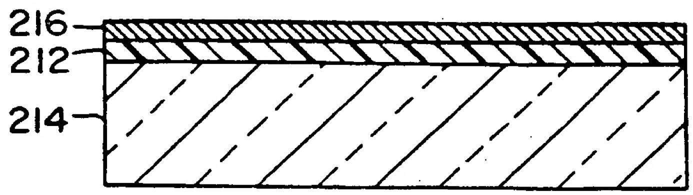


FIG. 8A

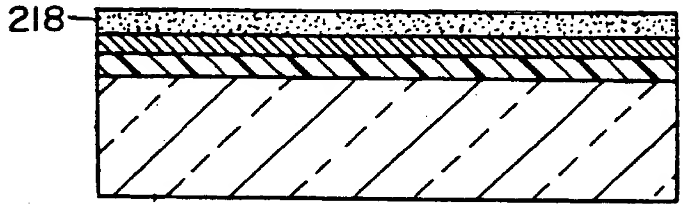


FIG. 8B

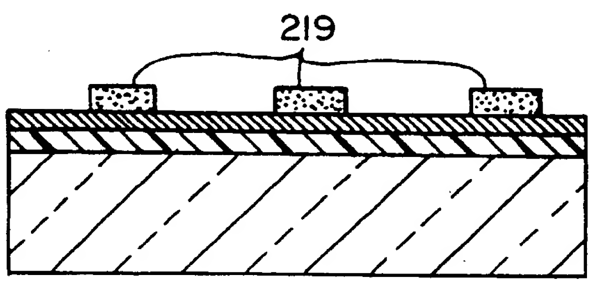


FIG. 8C

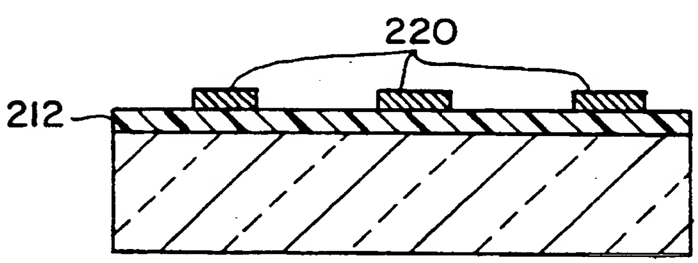


FIG. 8D

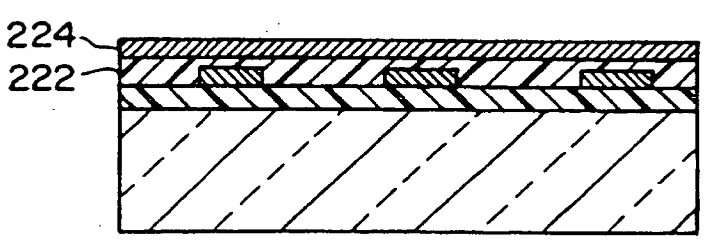


FIG. 8E

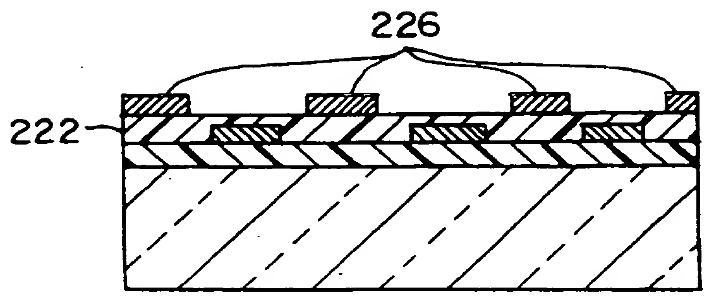


FIG. 8F

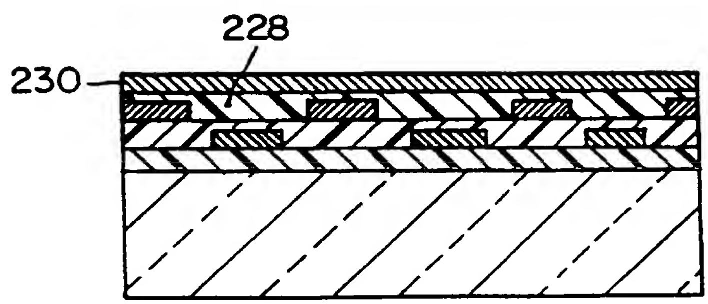


FIG. 8G

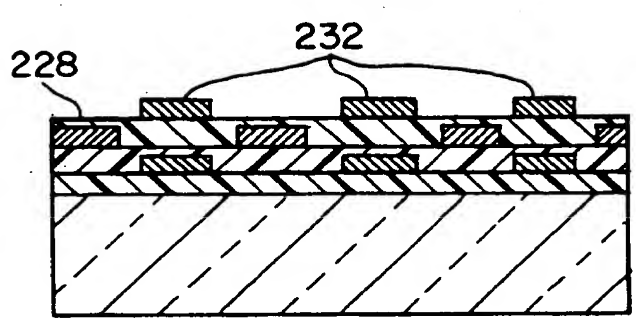


FIG. 8H

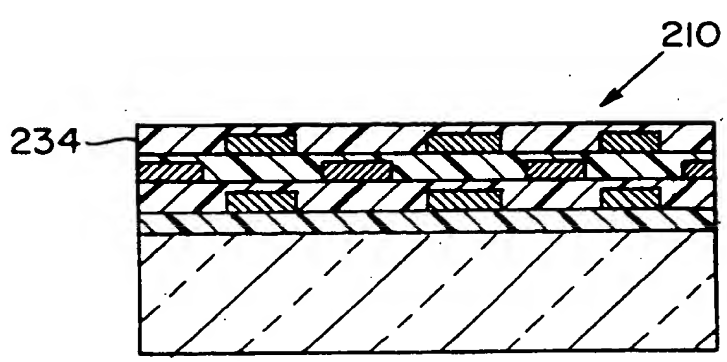


FIG. 8I

INTERNATIONAL SEARCH REPORT

Inter. nal Application No
PCT/US 96/03532

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B5/20 G02B6/12 H01S3/085 H01Q15/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G02B H01Q

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	PHYSICAL REVIEW, B CONDENSED MATTER., vol. 48, no. 23, 15 December 1993, NEW YORK US, pages 17576-17579, XP002009757 MCGURN ET AL: "Photonic Band Structures of two and three Dimensional periodic Metal or Semiconductor Arrays"	1
A	see the whole document	2,3,9, 12-14, 16,17

Y	US,A,5 281 370 (ASHER SANFORD A ET AL) 25 January 1994	1
A		3,9-11, 13-17
	see the whole document	

	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 August 1996	21.08.96

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Ward, S

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	APPLIED PHYSICS LETTERS, vol. 67, no. 15, 9 October 1995, NEW YORK US, pages 2138-2140, XP002010627 BROWN ET AL: "Large Electromagnetic Stop Bands in Metallodielectric Photonic Crystals" see the whole document ---	1-18
A	MICROWAVE AND OPTICAL TECHNOLOGY LETTERS, vol. 7, no. 17, 5 December 1994, pages 777-779, XP000578847 BROWN ET AL: "A New Face-Centered Cubic Photonic Crystal for Microwave and Millimeter-Wave Applications" see the whole document ---	1,4-7, 9-11, 14-18
A	WO,A,92 15124 (MASSACHUSETTS INST TECHNOLOGY ;LOCKHEED SANDERS INC (US)) 3 September 1992 see the whole document ---	1,3,9, 13,14, 16,17
A	US,A,5 385 114 (MILSTEIN JOSEPH B ET AL) 31 January 1995 see the whole document -----	1,9,14, 16,17

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter nal Application No
PCT/US 96/03532

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
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WO-A-9215124	03-09-92	US-A-	5187461	16-02-93
		AU-B-	1435192	15-09-92
		US-A-	5471180	28-11-95
		US-A-	5389943	14-02-95
US-A-5385114	31-01-95	NONE		